Chapter 5
Utilisation of Palm Oil Wastes for Biofuel and Other Value-Added Bio-Products: A Holistic Approach to Sustainable Waste Management for the Palm Oil Industry

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Abstract Conversion of agricultural wastes into biofuel and other value-added bio-products has not only benefited the environment but also helped reduce the dependency on natural resources leading to improved lifestyle of humankind. Palm oil wastes (OPW) comprising both solid and liquid residues from the palm oil industry are among the most abundant agricultural wastes in the world. The inefficient method of disposal and management of OPW has necessitated the need to recover value-added products from them. This study reviews the vital characteristics of OPW which present them suitable for the synthesis of value-added bio-products. Simultaneous production of palm oil fresh fruit bunches (FFB) and the utilisation of the plantation wastes for food and animal feed with integration of animal husbandry in the palm oil plantation are discussed. Moreover, the simultaneous conversion of FFB into palm oil and the utilisation of the mill's residues for value-added bio-products are also discussed.

Keywords Value-added bio-products • Palm oil wastes • Palm oil • Palm oil

5.1 Introduction

Due to uncontrollable global rise in population growth, there has been high demand for fuel, food, medicine, chemicals and other consumable products which have necessitated the growing interest in new technologies of transforming wastes into value-added bio-products. The conversion of agricultural residues such as palm oil wastes (OPW) into bio-products would help solve the issues of energy crisis, waste

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disposal and high phytochemical costs all over the world, hence achieving the holistic approach towards zero-waste strategy. This approach, for instance, has been adopted and applied by Haslenda and Jamaludin (2011) who have developed a framework called industry to industry by-product exchange network (I2IBEN) which is able to solve the problem of waste generation and management in the palm oil refinery. This framework is able to raise the palm oil refinery's gross profit to MYR182, 893 when the by-product revenue, packaging cost, delivery cost and all the supply constraints are considered.

The palm oil (*Elaeis guineensis* Jacq.) is a single-stemmed tropical and agro-industrial tree which belongs to the palm family (*Arecaceae*) and whose fruits produce mainly palm oil as the most consumed edible oil in the world (Kelly-Yong et al. 2007). The huge demand for palm oil (with about 27% share of the total world's oils and fats production) worldwide has caused an increase in oil palm production which has further facilitated the generation of large amount of OPW. These biomass residues are readily available and in urgent need of an efficient utilisation and effective means of disposal.

A hectare of palm oil plantation on dry weight basis generates about 50–70 tonnes of OPW annually (Salathong 2007). The main type of OPW includes empty fruit bunches (EFB), palm-pressed fibre (PPF), palm oil trunks (OPT), palm oil fronds (OPF) and palm oil mill effluent (POME), which are further discussed in this review. The world's total annual production of OPW is estimated at about 184 million tonnes with about 5% annual increment (Global oils and fats business magazine 2007). The palm oil industry generates its wastes mainly in the form of lignocellulosic materials from the plantation and the palm oil milling processes. The extraction of 1 tonne of crude palm oil (CPO) requires about 5 tonnes of fresh fruit bunches (FFB) which generates about 1.15 tonnes of EFB and 2.45 tonnes of palm oil mill effluents as residues (Corley and Tinker 2003). The processing of an FFB (weighing 20–30 kg) generates about 20% of CPO, about 25% nuts (comprising about 5% kernels, 13% fibre and 7% shell) and about 23% EFB (Yusoff 2006; Corley and Tinker 2003). These figures keep rising yearly as the demand for palm oil increases, and only about 10% of the generated OPW is utilised with the remaining 90% creating environmental burdens as their current disposal methods are unsafe. The development of new bio-products from OPW has gained much attention recently, and the simultaneous production of these products within the palm oil industry would help boost the economy and maintain sound environment.

The potential applications of OPW as raw materials for the production of value-added products such as sugar (Rahman et al. 2006; Chin et al. 2011; Zahari et al. 2012), phytonutrients (Ahmad et al. 2009; Ng and Choo 2010; Sasidharan et al. 2012), bioplastics (Mumtaz et al. 2010), biochemicals (Misson et al. 2009; Burham et al. 2009), herbal medicines (Sasidharan et al. 2010; Rosalina Tan et al. 2011) and biofuel (Jung et al. 2011; O-Thong et al. 2012) have been reported.

This review objectively elaborates on the potentials of utilising wastes through modern technological methods in transforming OPW into value-added bio-products as a way of enhancing sustainable utilisation and management of wastes from the palm oil industry as well as increasing the financial viability of the palm oil.

5.2 Characterisation of OPW Generated Through Various Operations in the Palm oil Industry

5.2.1 OPW from the Palm oil Plantation

5.2.1.1 Palm oil Fronds

Transplanting of palm oil seedlings, maintenance and harvesting of FFB as well as replanting of seedlings are the main processes which generate OPW within the plantation. Pruning and other field establishment and management processes (mostly after harvesting) generate large amount of palm oil fronds (OPFs) which comprise the petiole (about 6–8 m long) and the palm oil leaves (OPLs). Normally, after harvesting, the OPFs are left to rot in the plantation in order to fertilise the soil (Yusoff 2006). However, the huge amount of OPF generated globally may be considered underutilised as all of them may not be necessarily useful for nutrient recycling or soil conservation in the plantation. OPFs form the largest group of OPW (in the form of solid residue) whose total global generation capacity currently amounts to nearly 92.4 million tonnes (by dry weight) annually (FAO 2011). In Malaysia, for instance, in 2010 and 2011, about 54.17 million tonnes and 54.24 million tonnes of OPF alone were generated from the palm oil industry, respectively, compared to about 36 million tonnes in 2004 (Wan Zahari et al. 2004). Meanwhile, an estimate of about 56 million tonnes/year of OPF would be generated in Malaysia alone during the replanting process by the year 2020 (MPOB 2012).

The petiole of the OPF contains the fibre (mainly lignocellulosic materials) covered with a hard epicarp. OPF is found to contain high amount of carbohydrates which are convertible to simple sugars, biofuels, etc. OPF is reported to contain higher holocellulose (about 84% dry matter content comprising cellulose and hemicelluloses) compared to the fibres of pineapple leaves, coconut leaves and banana stem (Abdul Khalil et al. 2006). The acid detergent fibre (ADF) and neutral detergent fibre (NDF) of the OPF are found to be about 45.5% dry matter (DM) and 67.6% DM, respectively (Khamseekhiew et al. 2001). OPF contains about 13–37% lignin (Aim-oeb et al. 2008; Khamseekhiew et al. 2001), 5–12% crude protein, 2% fat (high in unsaturated fatty acids) (Hassim et al. 2010), 14–15% extractives and 2–30% sugar. Glucose is found to be the major sugar component in OPF juice in the range of 53.95 g/l. Other sugars in OPF include sucrose (20.46 g/l) and fructose (1.68 g/l) (Zahari et al. 2012). The nutrient and metal components of OPF fibre and OPF juice (or sap) have been reported by Zahari et al. (2012). OPF fibre and OPF juice contain sulphur (0.2% and 0.4%, respectively), phosphorus (0.02% for each), potassium (0.2% and 2.3%, respectively), calcium (1.4% and 2.9%, respectively), magnesium (0.2% and 0.5%, respectively), boron (4 ppm and 2 ppm, respectively), manganese (61 ppm and 2 ppm, respectively), copper (2 ppm for each), iron (100 ppm and 66 ppm, respectively) and zinc (3 ppm and 9 ppm, respectively). They also reported 174.11 μg/g total amino acids in the OPF juice comprising mainly of 111.0 μg/g serine, 22.7 μg/g glutamic acid and 27.1 μg/g proline.

5.2.1.2 Palm oil Leaves

OPLs are mostly referred to as the leaflets which are attached to the petioles of the OPF. OPLs are pinnate shaped of about 3–5 m in length with spines. OPL is composed of three parts, namely, the blade, the petiole and the base (Dransfield et al. 2008). An palm oil tree produces an average of 20 kg of dry leaflets yearly as wastes. As the age of the palm oil tree increases, the ratio of lengths of the OPL to OPF petioles decreases (Dransfield et al. 2008). For example, a 6-year-old palm oil tree has the ratio of OPL/OPF to be about 1.7 compared to 0.3 for a 21-year-old tree. This implies that the leaves of an older tree may have higher nutritional value compared to that of the petioles of the OPF (Dahlan et al. 2000).

The OPLs are found to have a better nutritive value compared to the OPF. They contain about 13% DM crude protein, more than 4% fat (Aim-oeb et al. 2008), 3.8% DM silica (Dahlan et al. 2000), about 60–68% holocellulose and 14% glucose (Abdul Khalil et al. 2006). OPL is found to contain more cellulose (35%) compared to that of neem tree (30%) and close to the same amount in wood (40–45%). The cell wall of the OPL contains moderate amount of crystalline cellulose mainly polysaccharides in the form of acetylated arabinoxylans (Abdul Khalil et al. 2006). The mineral contents of OPL as detected by Abdul Khalil et al. (2006) are about 2.62% nitrogen, 0.16% phosphorus, 1.25% potassium, 0.24% magnesium, 0.6% calcium, 0.55% chlorine and 0.22% sulphur. The vitamins A and E contents of OPL range from 1,900 ppm and 11,229–14,805 μg/g, respectively. These chemical characteristics of the OPL suggest a better option of its transformation into value-added products such as sugar and phytochemicals. However, after harvesting of the FFB, they are usually left in the plantation together with the OPF for only nutrient recycling.

5.2.1.3 Palm oil Trunk

Replanting of palm oil trees (mostly after 25 years of planting) contributes to the generation of huge amount of OPW in the form of palm trunks (OPTs). After replanting, the bole length of felled OPT may range between 7 and 13 m with a diameter of 45–65 cm taken at breast height (Abdul Khalil et al. 2010). After every replanting of palm oil trees throughout year, ~37 million tonnes of OPT is generated in Malaysia alone (Yusoff 2006). However, only about 40% are used for making plywood. The remaining 60% are discarded as OPWs which comprise core logs (50%) and veneers offcuts (10%) (Abdul Khalil et al. 2010). These materials could be utilised as feedstock for biofuel production and other value-added bio-products.

OPT comprises long vascular bundles which are surrounded by parenchyma tissues with numerous fibrous strands and vascular bundles. About 53.87% (dry weight) of OPT constitutes extractable fibre bundles, whilst the bark and parenchyma tissues form about 14% and 32% of the dry weight of the OPT, respectively (Abdul Khalil et al. 2010). These cells and tissues are packed with large quantities of holocellulose (about 45% cellulose and 25% hemicellulose), lignin (about 18%) and other extractives (about 10%) which can be fractionated, isolated and purified for value-added products. The sugar contents in OPT are about 35–48% glucose, 11–16% xylose, 0.50–0.63% galactose, 1.00–1.37% arabinose, 0.50–0.95% mannose and 0.20–0.023% rhamnose (Halimahton and Abdul 1990).

Other chemical constituents of OPT include fatty acid (<2%), 3% crude protein, 43.80% carbon, 6.20% hydrogen, 0.44% nitrogen, 42.65% oxygen, 0.09% sulphur and 6.87% ash (all at dry weights). OPT has an average density of 370 kg/m^3, moisture content of 55–83% and heating value of 19.26 MJ/kg (Nipattummakula et al. 2012).

5.2.1.4 Palm oil Roots

The palm oil roots (OPRs) have the fibrous (or adventitious) root system which comprises numerous, tiny moderately branched nonwoody roots growing from the base of the OPT. The primary roots of the OPR system are of constant diameter and emerge independently and periodically from an area at or near the base of the OPT called the root initiation zone (Dransfield et al. 2008). OPRs are usually isolated from the palm tree during replanting by using an excavator or a stump grinder. The OPR forms about 12% the total mass of the OPT at full maturity. Normally, OPTs are not felled together with the root system; hence, OPRs have not gained much attention for value-added products. However, the chemical characteristics of OPR show the presence of high amount of sugar or carbohydrate close to that of OPF with higher contents of extractives.

5.2.2 OPW from the Palm Oil Mill

5.2.2.1 Empty Fruit Bunches

EFB is a nonwood lignocellulosic material which forms about 23% of the total mass (or weight) of the FFB (Schmidt 2007). EFBs are the wastes (i.e. solid residue produced in largest quantity in the oil mill) obtained after stripping off the fresh palm fruitlets from the whole FFB. An EFB is made up of a main stalk (about 20–25% of the total weight of EFB) and numerous spikelets (about 75–80% of the total weight of the EFB) with sharp spines at their tips (Ahmad et al. 2009). The production of 1 tonne of CPO generates nearly 1.3 tonnes of EFB. Globally, about 42.3 million tonnes of EFB is generated by the palm oil industry annually (Kelly-Yong et al. 2007; Ahmad et al. 2009).

EFB vascular strands contain about 41.3–46.5% cellulose, 25.3–33.8% hemicellulose and 27.6–32.5% lignin (Sudiyani 2009; Piarpuzán et al. 2011). EFB sugar contents are about 2.5% galactose and 33.1% glucose (Abdul Khalil et al. 2006). Current research on the proximate and ultimate analysis of EFB by Mohammed et al. (2012) shows about 55.6% moisture content (by wet weight), 3.45% ash, 8.97% fixed carbon, 82.58% volatile matter, 46.62% carbon, 6.45% hydrogen, 1.21% nitrogen, 0.035% sulphur, 0.18% magnesium, 0.06% phosphorus and 45.66% oxygen in the EFB (Elbersen et al. 2005). The fatty acid content in EFB is <2% with its extractives and crude protein also constituting approximately 7.8% and 1–3.8%, respectively. Though the calorific value of EFB is between 17 and 19 MJ/kg (Ma and Yusoff 2005; Mohammed et al. 2012), a value slightly lower (due to high moisture and oxygen contents) than that for wood and coal (Demirbas 2004; Yang et al. 2006), it serves as a potential source of biofuel.

The inorganic contents (expressed in % ash, moisture free) of EFB have been analysed by Lahijani and Zainal (2011), Omar et al. (2011) and Mohammed et al. (2012) to consist of Si_2O (10.83–27.0), K_2O (34.7–53.73), CaO (1.9–12.5), MgO (4.8–8.75), Cl (3.6–5.3), Fe_2O_3 (1.28–3.6), Al_2O_3 (0.46–1.22), Na_2O (0.55–1.54) and P_2O_5 (1.12–3.6). EFB fuel density is about 1,420 kg/m^3 (Mohammed et al. 2012).

5.2.2.2 Palm-Pressed Fibre

PPF is an elongated fibrous (cellulosic) residue of palm oil fruits generated after oil extraction processes. PPF constitutes about 16% of the solid biomass of FFB. The strands of PPF which measure about 30–50 mm in length have been found to contain about 5–7% of residue oil after screw-press extraction of CPO (Choo et al. 1996; Sanagi et al. 2005).

Malaysia being the current world's leading exporter of palm oil generates about 12 million tonnes of PPF annually (Lau et al. 2008; Mazaheri et al. 2010). PPF is mainly combusted as a solid boiler fuel for the production of steam and electricity in the oil mill (Yusoff 2006).

The physico-mechanical properties of PPF include 150–500 μm diameter (Sreekala and Thomas 2003), 0.7–1.55 g/cm^3 density (Sreekala and Thomas 2003), 13.71% tensile strain, 3.38 μm cell wall thickness, 1.37 mg/m fibre coarseness, 55.43×10^{-4} rigidity index and 50–400 MPa tensile strength (Sreekala et al. 1997).

PPF contains about 39% fatty acid, 35% moisture content by wet weight, 75.99% volatile matter, 12.39% fixed carbon, 5.33% ash, 50.27% carbon, 7.07% hydrogen, 0.42% nitrogen, 0.63% sulphur and 36.28% oxygen (Azali et al. 2005). The heating value of PPF is about 20.64 MJ/kg. Considering sugar contents on dry basis, PPF consists of about 41–61% alpha cellulose, 42–65% cellulose, 17–34% hemicellulose, 13–25% lignin, 18–21% pentosan, 1.3% mannose, 2.5% arabinose, 33.1% xylose, 1.0% galactose and 66.4% glucose (Law et al. 2007; Abdul Khalil et al. 2006; Rozman et al. 2007). About 2.8–15% extractives can be obtained from PPF with 4,000–6,000 ppm of vitamin A and 2,400–3,500 ppm of vitamin E (Choo et al. 1996).

The inorganic composition of PPF expressed in % ash (moisture free) includes 3.54% Si_2O, 0.24% K_2O, 1.15% CaO, 0.13% MgO, 0.24% Fe_2O_3, 0.57% Al_2O_3 and 0.19% P_2O_5 (Chaiyaomporn and Chavalparit 2010). PPF fuel density is about 1,400 kg/m^3 (Mohammed et al. 2012).

5.2.2.3 Palm Oil Mill Effluent

POME is a thick concentrated dark brownish colloidal slurry (comprising water, oil and fine cellulosic materials) which is generated as the largest amount of liquid wastes (about 95% water and 5% solids) from the palm oil industry. POME is produced in the form of condensate and clarification sludge from two main processes in the oil mill, namely, sterilisation and clarification, respectively. The sterilisation of FFB, clarification of the extracted CPO and hydrocylone separation of the cracked mixture of kernel and shells contribute about 36%, 60% and 4% of POME, respectively, in the oil mill (Sethupathi 2004). With about 1.5 m^3 (or about 1.5 tonnes) of water used in processing 1 tonne of FFB, about half of this quantity (~0.50–0.75 tonnes water) comes out as POME (Alam et al. 2009). In 2004, for instance, about 40 million tonnes of POME was generated from about 372 palm oil mills in Malaysia (Yacob et al. 2005). This figure rose drastically to about 53.1 million tonnes in 2006. Generally, for every tonne of CPO produced, about 3.25 tonnes of POME is generated (Corley and Tinker 2003).

POME contains about 40,500 mg/l total solids (comprising cellulosic materials) and 4,000 mg/l fats, oil and grease (Ma 2000) depending on the method of oil extraction and the characteristics of the FFB. The pH of POME ranges from 4 to 5, whilst its temperature of POME may vary from 80 to 90°C (Ma 2000) due to heat production during the sterilisation and other mechanical processes within the palm oil mill. The biological oxygen demand (BOD) and chemical oxygen demand (COD) of POME are very high exceeding 25,000 mg/l and 50,000 mg/l, respectively; hence, they are considered more polluting than domestic sewage (Ma 2000).

POME contains dissolved substances such as protein (about 9.6% DM), carbohydrate, nitrogenous compounds (ammonical nitrogen of 20–40 mg/l and total nitrogen of 100–1,200 mg/l) and fats which can be converted into useful materials using microbial processes (Ma 2000). POME contains about 11% cellulose, 7% hemicellulose and 42% lignin on dry basis (O-Thong et al. 2012). The amount of minerals such as phosphorus (about 0.26%), magnesium (about 0.25%) and calcium (about 0.28%) which are found in POME is good for healthy plants' growth. Muhrizal et al. (2006) reported that POME contains high content of aluminium as compared to that of chicken manure and composted sawdust. POME has been reported by Habib et al. (1997) to contain low concentrations of lead (about 17.5 μg/g) due to the contaminations from the paints and glazing materials used on plastic and metal pipes and tanks in the oil mill.

5.2.3 *OPW from the Palm Kernel Crushing Unit*

5.2.3.1 Palm Kernel Shells

In the palm oil mill, after the hydrocyclone separation process, the palm nuts are sent to the crushing unit where they are dried and cracked, whilst the PPF are sent to the boiler. The cracked shells without the kernel or seeds are called palm kernel shells (PKS). PKS can be described as the hard endocarps surrounding the palm kernels or seeds which are obtained after the residual nuts from the screw press are mechanically crashed to extract the seeds or kernels.

Presently due to increase in palm oil production, the world's annual generation of PKS is estimated at 11.1 million tonnes as compared to 2.52 million tonnes and 4.3 million tonnes in 2004 and 2006, respectively (MPOB 2012). Because PKS possess high solid content (with a calorific value of about 22.14 MJ/kg), low sulphur (about 0.09% dry weight) and low ash (about 3% dry weight) contents, they are often used as fuel for the power plants in the palm oil industry (Yusoff 2006). However, nearly 40% of these wastes are utilised by the oil mill for power generation; the rest are dumped in open space in the crushing unit and sometimes incinerated in an uncontrolled manner within the industry contributing to significant environmental pollution.

The proximate and ultimate compositional analyses carried out by Sukiran (2008) show that PKS contains about 30% moisture content by wet weight, 73.74% volatile matter, 18.37% fixed carbon, 2.21% ash, 53.78% carbon, 7.20% hydrogen and 36.30% oxygen. The inorganic composition of PKS expressed in % ash (moisture free) includes 2.96% Si_2O, 0.60% K_2O, 0.48% CaO, 0.83% MgO, 0.08% Fe_2O_3, 0.24% Al_2O_3 and 0.59% P_2O_5 (Chaiyaomporn and Chavalparit 2010). The fuel density of PKS is about 1,430 kg/m^3 (Mohammed et al. 2012).

The holocellulose compositions of PKS are about 20.8% cellulose and 22.7% hemicellulose with lignin content of about 50.7% (Saka 2005).

5.2.3.2 Palm Kernel Cake

Palm kernel cake (PKC) is the by-product or solid residue resulting from the mechanical screw pressing of palm kernels which contains some residual oil. In Malaysia alone, ~2.2 million tonnes of PKC were produced in 2007 which increased to about 2.4 million tonnes in 2009 (MPOB 2012) due to expansion of the palm oil industry. The global generation capacity of PKC in 2011 was estimated at 3.5 million tonnes (MPOB 2012).

PKC is being used currently as fattening steers in feedlots (Akpan et al. 2005). Depending on the amount of PKS in the PKC, crude protein content of PKC may range from 160.0 to 180 g/kg DM. PKC again contains high amount of minerals including copper an. zinc which have no significant disadvantage (such as mortality in ruminants fed with PKC) as reported by Hair-Bejo et al. (1995). PKC contains about 78% hemicellulose in the form of mannan and 12% cellulose (Sundu and Dingle 2003).

PKC has dry matter content of 883 g/kg DM, 126–131 g/kg DM extractives, 39.4 g/kg DM ash content,131 g/kg DM crude fibre, 460.5 g/kg DM ADF and 682 g/kg DM NDF (Ramachandran et al. 2007; Akpan et al. 2005). PKC has been analysed by Ogbuagu (2008) to contain high values of carotenes or vitamin A (0.16 mg/100 g), thiamine (0.07 mg/100 g), riboflavin (0.07 mg/100 g), nitrates (3.05 mg/100 g) and nitrites (0.29 mg/100 g).

5.2.4 *OPW from the Crude Palm Oil Refining Unit*

5.2.4.1 Palm Fatty Acid Distillate

Palm fatty acid distillate (PFAD) is a highly odoriferous by-product (comprising mainly glycerol esters) obtained from the refining of CPO whose main processes include phosphoric acid treatment, bleaching earth treatment, deacidification and deodorisation of CPO (Ab Gapor 2010). At room temperature, its state is solid but becomes liquid on heating at elevated temperatures. Deacidification removes the free fatty acids, whilst deodorisation removes the odour by steam distillation under high vacuum. The distilled fatty acid is known as PFAD. In Malaysia, about 0.63 and 0.71 million tonnes of PFAD were produced in 2006 and 2008, respectively (Ab Gapor 2010).

PFAD has a moisture content of 0.03–0.24%, 80–90% free fatty acid in the form of palmitic acid, 1.1–2.3% unsaponifiable matter, density of 0.8640–0.8880 kg/l, iodine value of 46.3–57.6 I_2/100 g and saponifiable value of 200.3–249.4 mg KOH/g PFAD (Bonnie and Mohtar 2009). Other constituents of PFAD include glycerides (14.4%), squalene (0.8%), vitamin E (0.5%), sterols (0.4%) and other extractives (2.2%) (Bonnie and Mohtar 2009; Hamirin 1983).

Figure 5.1 summarises the generation of OPW from the production of 5 tonnes of FFB and a tonne of CPO.

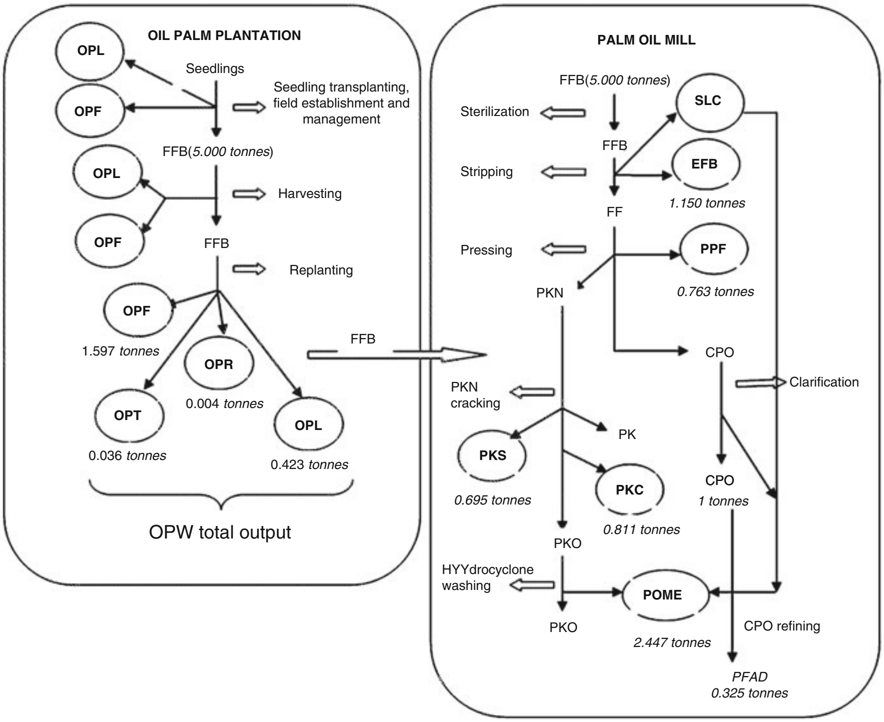

Fig. 5.1 Schematic diagram of OPW generation in the palm oil industry

5.3 Value-Added Bio-Products from OPW

5.3.1 Food and Animal Feed

Though OPWs have been considered as nonedible, the potential of producing highly nutritious foods (for both humans and animals) as well as vitamin supplements has been reported in recent studies. The fibres of the OPW (mostly EFB, OPT and OPF) comprise mainly cellulose (about 25–50%), hemicellulose (about 20–35%) and lignin (about 15–25%) which are readily convertible to carbohydrates and sugars such as glucose, sucrose and fructose for various applications in the food industries.

EFB is reported to compose of about 24% xylan (a sugar polymer made of pentose sugar called xylose) which can serve as a substrate for the production of sweetening agents such as xylitol, sorbitol, and lactitol by catalytic hydrogenation (Wyman 1994; Silva et al. 1995). Xylitol is used extensively in the food and pharmaceutical industries as sugar for diabetic patients, as supplements in energy drinks and as anticariogenic agent in toothpaste formulations for the prevention of cancer (Makinen 1992). Aqueous sorbitol solutions are hygroscopic thus useful in the applications of humectants and softeners in the food and pharmaceutical industries (Gliemmo et al. 2008). Recent studies have reported the hydrolysis of xylose and glucose from sulphuric acid-pretreated EFB with concentrations of 31.1 and 4.1 g/l, respectively (Rahman et al. 2006), steam-pretreated OPF with glucose yield of 92.78 wt% (Goh et al. 2010), steam-pretreated EFB with glucose yield of 209 g/kg EFB (Saleha et al. 2012), the juice from the OPF (Fazilah et al. 2009) with glucose concentration of 53.95 ± 2.86 g/l, thermally treated OPT (Ho et al. 2007), etc. OPT juice has been found by Chin et al. (2011) to have a higher glucose conversion yield compared to those for rubberwood sawdust and mixed hardwood sawdust. The highest yield of monomeric sugar (70% of total carbohydrate content) was found in EFB (41.82%, w/v) pretreated by enzyme and saccharified for 120 h (Rashid et al. 2011). Food flavouring such as vanilla essence can be extracted from EFB (Ibrahim et al. 2008).

PPF is used as fibre enrichment agent for the manufacture of bread which gives it a heavier consistency than normal white bread (Kamarun Zaman 2008). Fibre content of 6.1 g/100 g serving has been used in a formulation of the palm fibre bread which has the same fibre content as most whole meal breads. Pre-hydration of OPW fibres was reported to improve dough water absorption and high fibre bread loaf volume (Kamarun Zaman 2008). Again, OPT fibres, due to its high water absorption rate (without congealing) coupled with its capability of withstanding high temperatures during food processing, have been successfully used as food fibre in yoghurt, pastries and bread in place of wheat. Currently, Malaysia produces special cereals from OPT fibres using patented process by the Sukhe International Sdn Bhd. Thus the transformation from wastes to wealth is highly feasible. PKC contains valuable dietary protein (14.5–19.5 g/100 g) (Alimon 2004) which can be commercially isolated (by enzyme-assisted extraction in alkaline medium with an optimum yield of 11.91 g/100 g) and concentrated for various applications in the food industry (Chee et al. 2012). PKC is also used as a substrate in solid-state fermentation (SSF) for the production of enzymes such as tannase (Sabu et al. 2005), phytase (Ramachandran et al. 2005), alpha amylase (Ramachandran et al. 2004), and β-mannanase (Ong et al. 2004). Ariffin et al. (2008) have also reported the feasibility of producing an enzyme called bacterial endoglucanase from EFB for different applications in the food and nutraceutical industries.

Flour prepared from defatted PKC was used as a substitute for wheat bran for the preparation of dietary fibre-rich wheat cookies and bread. These cookies and bread from PKC showed better nutritive value (e.g. lower starch content) than those for normal wheat bread and cookies (Pacheco de Delahaye et al. 1994). The feasibility of monoacylglycerol production from PFAD as additives in bread and pastries has also been demonstrated by Junior et al. (2012) with a production yield of 73%.

The low protein and high fibre contents of OPF make it a good potential source of feed for many classes of herbivorous animals like cattle, buffaloes, sheep, etc. (Dahlan et al. 2000). The potential of using PPF for ruminant production has been examined by Abu Hassan et al. (1996) to be feasible especially when it is chemically treated and well formulated to improve its nutritive value. Various pretreatment methods have been used to improve the quality of PPF to enhance its biodegradability and digestion in ruminants (Abu Hassan et al. 1996; Dahlan et al. 2000). Experimental goats were given OPF as a raw feed whose organic matter digestibility increased through ensiling, while pelleting increased the intake rate significantly (Dahlan et al. 2000; Kawamoto et al. 2001). PPF treated with sodium hydroxide has been reported by various studies (Kawamoto et al. 2001; Jelan et al. 1986) to increase its dry matter digestibility from 43.3% to 58.0% but detrimental to its palatability. Low-pressure steaming of OPF at 10 kg/cm^2 for 20 min followed by oven drying at 60°C for 48 h have been reported by Bengaly et al. (2000) to significantly improve its nutrient degradability. Urea treatment (3% and 6%) had a negative effect on digestibility, but the addition of up to 3 g/kg of urea to steam-treated OPF increased its intake and digestibility in goats (Abu Hassan et al. 1996). However, in sheep, coupling urea treatment with heat treatment of OPF showed better intake and digestibility up to 16 g/kg (Bengaly et al. 2010).

Diets containing about 50% OPF which were ministered to cattle did not show any nutritional disorders as side effects (Abu Hassan et al. 1996). Goto et al. (2002) have reported low contamination risks in OPF as they are poor medium for aflatoxin (a food contaminant) production. Though much research have not been done on the use of EFB as feed for animals, Abu Hassan et al. (1996) have concluded that EFB processed into pellets may increase the nutritional value of the feed. The sustainable utilisation of fibres from the OPF, PPF and EFB is achieved when they are made into pellets. For instance, unpelleted or untreated OPF petioles are not palatable to goats (Dahlan et al. 2000). Cattle fed on OPF pellets measuring 9 mm in diameter and 3–5 cm in length with 33.3% total digestible nutrients gained 0.93 kg/day (Asada et al. 1991).

In order to maintain the availability of animal feed all year round, fibres from the OPW can be used in place of grass molasses and straw especially during the dry season when they get dried up. Also, the use of OPW fibre may save a lot of time used in grazing for ruminants (Abu Hassan et al. 1996). The integration of livestock rearing in oil palm plantation which result in internal food chain (i.e. OPFs, EFBs, OPLs, PKC etc. are used to feed the animals whilst the dung from the animals are also used to fertilize the plantation's soil) may provide cost effective utilization of OPW.

Mixtures of OPW such as OPF (about 30%) and PKC (about 70%) which were administered to cows as feed increased their milk production more than the feed containing only grass (Abu Hassan et al. 1996). Rabbits fed on 50% pelleted OPF and 50% concentrate gained about 28.3 g/day (Dahlan et al. 2000). Abu Hassan et al. (1991) have shown that OPT fibre is a good source of roughage for ruminants compared to rice straw.

5.3.2 Phytochemicals (Nutraceutical and Pharmaceutical Products)

Phytochemical analysis of OPW by various researches has revealed the presence of several important bioactive compounds such as carotenoids, phenolic compounds, sterols and polysterols, tocols, coenzyme Q10 and squalene whose pharmacological activities are beneficial for healthy body growth. Quantification and isolation of these phytonutrients have successfully been done through various technologies such as high performance liquid chromatography (HPLC). OPW phytochemicals are found to enhance the body’s immunity and promote would healing with most of them possessing antioxidant, anticariogenic and anti-hypertensive activities.

Various extracts from the OPW have been reported by Yap et al. (1991) to contain about 13 different types of carotenoids with the major ones being α-carotene, β-carotene, γ-carotene lycopene and phytoene which help maintain healthy body tissues and prevent xerophthalmia (night blindness) (Choo et al. 1992; Ooi et al. 1994).

The residual oil from PPF contains almost six times the amount of carotenoids (4,000–6,000 ppm) found in CPO (500–800 ppm) (Choo et al. 1992, 1996). The carotenoid concentration is even higher in PPF residual oil from hybridised palm oil species (6,000–7,000 ppm) (Choo et al. 1996). This implies that, presently, due to technological advancement, most of the palm oil fresh fruits produced are from hybrid species hence more carotenoids from the PPF. Carotenoids from PPF have again been quantified and isolated by various recent authors with concentrations of about 2,922 mg/kg compared to 800–1,000 mg/kg for CPO (Lau et al. 2005, 2006, 2008; De Franca and Meireles 2000) using various separation and extraction techniques such as the HPLC. The presence of carotenoids in the membrane cell of PPF which could not be completely extracted during CPO extraction is said to account for the higher carotenoids in PPF. This could mean that the fibres of OPW present potential sources of carotenoids in large quantities. The tocols in PPF include α-tocopherols (55.3% and higher than that of CPO with 24.4%), α-tocotrienols (11.4%), γ-tocopherols (3.5% and higher than that of CPO with 1.7%), γ-tocotrienols (21.0%) and δ-tocotrienols (8.8% and higher than that of CPO with 7.6%) (Ng et al. 2004; Choo et al. 2005; Han et al. 2004). The approximate concentrations of tocols found in PPF as reported by various authors are 2,000–4,000 ppm compared to 600–1,000 ppm for CPO (Choo et al. 1996; Ng et al. 2004) and 3.7–4.0 mg/ml (Sanagi et al. 2005). PPF contain about 500–1,000 ppm of squalene (Choo et al. 2005), about 1,000–1,500 ppm coenzyme Q10 compared to 10–100 ppm in CPO (Ng et al. 2004) and about 2.6 wt% and 3.0 wt% glycolipids and phospholipids, respectively (which is higher in chloroform/methanol extracts at 6 wt% and 10 wt%, respectively) of the total lipids extracted.

OPL extracts contain about 1,900 ppm carotenoids (Ng and Choo 2010), $1.71 \times 10\ m^3$ tocols (mostly tocopherols) per kg dried OPL (Birtigh et al. 1995), 11,229–14,805 μg α-tocopherol per g OPL (Kato et al. 1983) and 30–44 μg β-tocopherol per g OPL using the technologies of combined gas chromatography–mass spectrometry and thin layer chromatography (Kato et al. 1983). Flavonoid content of OPL extracts has antioxidant effects (analysed by 2,2-diphenyl-2-picrylhydrazyl (DPPH) assay) in the range of 56–93% OPL which help heal free radical-mediated diseases such as cancer (Ng and Choo 2010), anti-hypoglycaemic effect (against alloxan diabetic rats), anti-hyperlipidemia effect (Sasidharan et al. 2010, 2012; Syahmi et al. 2010) and antimicrobial activity (Sasidharan et al. 2010). In most parts of Africa, OPR and OPL water extracts have been used in treating malaria and typhoid fever. The OPW fibres are also milled and made into pastes which are used in treating boils, skin diseases and wounds.

The antioxidant effect of OPF extracts (203 μmol) is found to be higher compared to that of green chilli (43 μmol), papaya shoot (58 μmol) and lemon grass (22 μmol) (Abeywardena et al. 2002). PKS pyrolysate has been analysed by Ukoh et al. (2004) to exhibit high antibacterial effects hence the need to extract phytochemicals from PKS which is considered wastes in the palm oil industry.

POME extracts contain about 287–1,665 ppm carotenoids. Ahmad et al. (2009) have reported that about 284,000 tonnes of oil extractable from POME could produce about 140,000 kg carotenoids. The presence of significant amounts of phenolic compounds (mostly flavonoids) in POME has been reported by various authors (Rakamthong and Prasertsan 2011; Omayma et al. 2009), and their antioxidant activities are also analysed by Yun et al. (2008). A sustainable utilisation of POME for phytonutrients would be achieved through simultaneous production of POME and extraction of phytonutrients to supplement those in CPO by means of a series of innovative separation techniques which would isolate specific compounds of interest on the basis of their molecular weights (Sundram et al. 2003).

Through molecular distillation process, PFAD is found to contain about 3.94% (Sarunya et al. 2006) and 2,000–8,000 ppm (Choo et al. 2005) of squalene, 6.63%

tocotrienols, 2.20% α-tocopherol and 4.77% sterols (Posada et al. 2007). Chu et al. (2004) have also detected various sterols in PFAD including 13.7% ergogst-5-en-3-β-ol(2,2-dihydrobrassicasterol), 6.27% 2,2-stigmasta-5,2,2-dien-3-β-ol (stigmasterol) and 80% stigmast-5-en-3-β-ol (sitosterol).

Cinnamic derivatives and flavones in OPR and palm oil fibre (which may include fibre from OPT, OPF and EFB) were detected at 280 nm (Akpan and Usoh 2004), whilst flavonones, chlorogenic derivatives and flavones were also detected at 350 nm (Diabate et al. 2009).

Extracts from PKC contain about 5.5 ppm sterols consisting of 7-α- and 7-β-hydroxy derivatives of β-sitosterol, stigmasterol, campesterol and phytosterol oxides (7-keto-β-sitosterol) (Bortolomeazzi et al. 2003) and 2.3 g/kg saponins which are higher than the saponins found in chickpea (2.3 g/kg) (Ogbuagu 2008).

D-Mannose (a hexose which is used as food additive or supplements in many applications in the pharmaceutical industry) has been isolated from PKS and purified for the prevention of bacterial infections (Zhang et al. 2009).

Many types of organic acids have been produced from OPW including lactic acid from OPT (Kosugi et al. 2010; Chooklin et al. 2011), acetic, propionic, butyric and lactic acids from POME (Ali Hassan et al. 1996) and citric acid from EFB (Bari et al. 2009) which are used as additives in the food, pharmaceutical and cosmetics industries.

5.3.3 *Biofuels*

Both the OPW in the form of solid and liquid residues can serve as a source of raw material for biofuel production. In order to enhance the physical and chemical composition of OPW fibres for energy production, gasification, pelletisation (or briquetting), torrefaction and liquefaction have been applied. The heating value of OPF presents it appropriate for use as pelletised fuel which could be mixed with glycerol to enhance its heating value (Azuan 2008). Research on the production of high-quality briquette fuel produced by the mixing of 100% pulverised EFB with sawdust or PKS (also called palm kernel expellers) have been carried out (Nasrin et al. 2008). High-energy solid fuels have been produced from pelletised PKC (Razuan et al. 2011), briquetted PKS and PPF (Husain et al. 2002) and torrefacted EFB (Uemura et al. 2013). The energy content of torrefacted fuels from wheat straw, reed canary grass and willow as reported by Bridgeman et al. (2008) are 77%, 78% and 86%, respectively, which are lower than that for EFB (85–95%), PPF (96%) and PKS (100%) (Uemura et al. 2013). PKS is widely used traditionally as solid fuel (or pelletised fuel) by black and goldsmiths in most part of Africa. It can also be mixed with other grades of biomass for co-firing with steam or used in biomass power plants.

The BOD of POME could be reduced (to <100 mg/l) when treated in ponds and digesters for the production of biogas. For every ton of POME generated in the palm oil mill, about 12.36 kg of methane could be generated from it (Basri et al. 2010).

In Malaysia and Thailand, large quantities of generated POME are used as feedstock for biogas production (Basri et al. 2010). In order to promote sustainable utilisation of OPW in the palm oil mills for value-added products, the feasibility of biogas production from EFB and its co-digestion with POME have been investigated by O-Thong et al. (2012). Co-digestion of EFB with POME is found to enhance microbial biodegradability and increase-methane yield (by 25–32% higher) at mixing ratios of 0.4:1, 0.8:1 and 2.3:1 on volatile solid basis than digesting EFB alone or POME alone (O-Thong et al. 2012). A further optimisation study on the improvement of biogas and methane yields from the digestion of a mixture of POME and EFB has been done by Saleh et al. (2011). The optimal conditions to obtain about 25.6% methane were 47.8°C with 50.4 ml POME and 5.7 g EFB. EFBs again have been improved (through NaOH pretreatment for 60 min) to produce biogas with methane yield of 0.404 Nm^3/kg (volatile solids) which accounts for about 97% of the theoretical yield of methane from carbohydrates (0.415 Nm^3/kg carbohydrates) (Nieves et al. 2011; Davidsson 2007).

Bio-oils are found to be promising candidates for petroleum fuel replacement which are applicable in various thermal devices. The production of bio-oil from OPW such as EFB (Misson et al. 2009; Abdullah 2005; Abdullah and Gerhauser 2008; Lim and Andrésen 2011; Sulaiman and Abdullah 2011), PKS (Abnisa et al. 2011; Kim et al. 2010; Salema and Ani 2011), OPF (Lim and Andrésen 2011), PPF (Salema and Ani 2011) and PKC (Razuan et al. 2010) by pyrolysis has been reported. Bio-oil yields of 46.1 wt% (at 500°C pyrolysis temperature for 1 h with a particle size of $1.7 < dp < 2$ mm), 80–90 wt% (pretreated with NaOH and H_2O_2) and 42.3% (with sub/supercritical treatment with 1,4-dioxane at 290°C) have been produced from PKS (Abnisa et al. 2011), EFB (Misson et al. 2009) and PPF (Mazaheri et al. 2010), respectively. Abdullah and Gerhauser (2008) have concluded that the fast pyrolysis of washed EFB with a low ash content produced bio-oil which had similar yields as that mostly obtained from wood. Again, the characterisation of EFB bio-oil by Pimenidou and Dupont (2012) indicates better hydrogen yield (15.9 wt%) via steam reforming compared to that of pinewood (13.7 wt%).

Various effective catalysts such as calcined dolomite have been proven to be a viable catalyst which improves hydrogen production and reduces the amount of tar generated in syngas produced from OPW solid residues (Mohammed et al. 2012). The low moisture, high volatile matter, low fixed carbon and ash contents of EFB make it highly volatile and reactive (Demirbas 2004) and highly appropriate for the production of gas fuel. The pyrolysis of PKS for the production of hydrogen using nickel and La/Al_2O_3 at 900°C in a fixed bed reactor yielded 37.28 vol% and 38.45 vol%, respectively (Yang et al. 2006). Bio-hydrogen production from the hydrolysate of microwave-assisted sulphuric acid-pretreated OPT has been reported (Khamtib et al. 2011). Steam gasification (at 800°C) of OPT yielded more syngas (50%), energy and hydrogen (60%) (Nipattummakula et al. 2012) than those from mangrove wood, paper an. food waste (Nipattummakula et al. 2012; Ahmed and Gupta 2009). The EFB generated as wastes from the palm oil mill after processing about 60 tonnes of FFB every hour is estimated to be capable of producing about 3 MW of electricity (from controlled gasification process). Pattanamanee et al. (2012) have concluded that EFB presents an efficient OPW for producing bio-hydrogen by anaerobic photo-fermentation with an isolated photosynthetic bacterium *R. sphaeroides S10*.

The production of bio-alcohols such as ethanol from EFB (Tan et al. 2010), ethanol from OPT (Yamada et al. 2010), ethanol from PKC (Cerveró et al. 2010), butanol from EFB (Noomtim and Cheirsilp 2011), butanol from POME (Hipolito et al. 2008), butanol from PPF (Ponthein and Cheirsilp 2011) and ethanol from POME (Alam et al. 2009) through various processes prior to various pretreatment methods such as acid and enzymatic pretreatments. A million tonne of EFB would have the potential to produce about 81×10^3 kl of ethanol (Shinichi et al. 2009). Also, OPT has the potential of producing higher ethanol yield (9.5–10.3 kl/ha) compared to that of sugarcane bagasse (4.5–7.2 kl/ha) (Mori 2007). An average-weighted OPT could produce about 107.8 kg and 123.5 kg fermentable sugars from the sap and solid fibres, respectively, which can produce about 69.8 l and 41.4 l bioethanol, respectively (Mori 2007). Simultaneous saccharification and fermentation (SSF) of OPT fibre for bioethanol production gave a yield of 78.3% making OPT a potential source of raw material for bioethanol production (Jung et al. 2011). PKC which is readily available from palm kernel crushing units contains large amount of mannan (which is about 35.2% of the total carbohydrates in PKC) which can be easily hydrolysed into sugar for the production of bioethanol (with yield of 125 g/kg PKC) without any pretreatment (Cerveró et al. 2010).

Biogas, bio-oil, bio-hydrogen, etc. which are produced from OPW can be used to generate electricity in order to reduce the dependency on fossil fuel used by power plants as well as safeguarding the environment. For instance, in Malaysia, it is estimated that for a million ton of FFB processed, about 16,000 GW/year of electrical energy can be generated from the OPW produced (Low 2011).

5.3.4 Pulp and Paper

The expansion of the palm oil industry coupled with the high population growth resulting in high demand for pulp (for tissue and papermaking) has ended up in the research for more sustainable OPW conversion methods into these value-added products. Through various processes, pulp has been produced from the fibres of OPF (Wanrosli et al. 2007; Zainuddin et al. 2011), EFB (Martín-Sampedro et al. 2012; Jiménez et al. 2009; Rodríguez et al. 2008) and OPT (Sun and Tomkinson 2001). Sun and Tomkinson (2001) have reported that about 93.6% of the total lignin (with a purity of 98.8%) in OPT can be recovered from the supernatants of the black liquor of the OPT fibre after isolation of the polysaccharide degradation.

The appropriate morphological characteristics of OPF (compared to those of wood) such as higher rigidity index (83.16 μm), thick cell wall (3.97 μm), lower lignin content, high fibre diameter (19.6 μm), high lumen width (11.66 μm) and coarseness (0.098 mg/m) make it a good source of pulping material (Mohammad Izzuddin Bin 2008). The lower lignin content makes it easier to be chemically pulped, whilst the cell wall thickness gives it a sheet of higher bulk (making its sheets not to collapse easily) and lower interfibre bonding potential compared to those of hardwood like aspen (Law and Jiang 2001) and eucalyptus (Alcaide et al. 1990).

EFB can also be chemically pulped to produce high purity unbleached cellulose pulp by water pre-hydrolysis treatment and soda pulping (Wanrosli et al. 2003; Leha et al. 2008). Recently, an effective patented method of producing recycled bleached mechanised pulp (RBMP) from EFB has been developed by 1 Green Enviro Sdn Bhd (a company in Malaysia). This method is capable of producing pulp from EFB at a cost of US$2.70 per metric tonne compared to the cost of producing it from 20% softwood pulp and 80% old corrugating cartonnes (US$307.50 per metric tonne). It has also been reported by the Malaysian Timber Council (MTC) that for every 5 tonnes of EFB produced, about 1 tonne of pulp could be obtained from it.

5.3.5 Bio-Fertilisers and Bio-Composts

The production of bio-fertilisers and bio-composts is an environmentally friendly way of overcoming the disposal problems of organic wastes especially OPW which are in abundance. The innate fabric of the fibres of OPW is tough and hence very difficult to decompose. However, recent researches have come out with different effective ways of composting and preparing bio-fertilisers from these wastes via enzymatic and chemical means. Most often, PKC is used to enhance the fibres' decomposability due to their good nutrient contents for making fertiliser. PKCs consist of 6.0% P_2O_2, 11.0% K_2O, 13.5% CaO, 3.5% MgO and 7.5% SO_2 (Mohammad et al. 2012). An experiment to investigate the growth of palm oil seedlings using the same quantities of bio-fertiliser from PKC, normal chemical fertiliser and a control (no fertiliser application) gave frond lengths of 62.03 cm, 53.42 cm, and 28.85 cm, respectively. The petiole dry weights recorded were 0.30 g, 0.25 g, and 0.28 g, respectively (Henson and Dolmat 2003). This clearly shows the high preference of bio-fertiliser from PKC for healthy plant growth. The overall nutrient contents of OPW fibres and PKC make them appropriate for the preparation of bio-fertilisers and bio-composts which many studies have reported (Mohammad et al. 2012; Baharuddin et al. 2009).

POME is also commonly blended with other OPW fibres for composting and fertilisers. Kala et al. (2009) have tested the potency of blending OPT, EFB and OPF with POME for compost to be highly effective. OPT (with POME 4:1 w/w) was found to exhibit properties of a very good compost as potting media for ornamental plants. However, POME alone has been efficiently used for making fertilisers or composts (Siregar et al. 2002) through optimised solid-state fermentation with thermophilic fungus, *Chaetomium* sp. (Yaser et al. 2007).

The fibres from OPW have also been used individually for making composts. EFB is bulky; thus, in order to reduce its bulkiness and make it easier to handle, they are compressed into mats usually called Ecomat (Sung et al. 2010). Ecomat is also found to improve the decomposition rate of the wastes hence producing efficient compost. EFB has fertiliser contents (expressed in kg/ton EFB) of 3.8 kg urea, 3.9 kg rock phosphate, 18.0 kg muriate of potash and 9.2 kg kieserite (Singh et al. 1999) whilst OPF contains 4.4 kg of kieserite, 19.3 kg of muriate, 2.8 kg of rock phosphate and 7 kg of urea/ton (Sung et al. 2010). Compost made from EFB with *Trichoderma* sp. and supplemented with nitrogen has proven to be of same nutrient values and biodegradability as compared to chicken manure when they were tested on tomato plants (Mukhlis 2006). Pruned OPFs that are used as mulch as well as for soil conservation in the plantation are found to contribute directly to the supply of phosphates and indirectly by reducing the phosphate sorption capacity in soils (Fairhurst 1996).

5.3.6 Furniture and Palm-Wood Building Materials

The shortage of wood (due to resource depletion) for furniture coupled with its high and fluctuating costs has increased the zeal for many researchers to seek for alternatives. OPW in the form of solid residues such as EFB, OPT and OPF have been used currently in producing good quality furniture (Abdul Hamid et al. 2005). The high-density gradient which exists along the radial and longitudinal direction of the OPT makes it less attractive to be used either as lumber or plywood (Loh et al. 2011). However, other studies have improved upon these properties to make OPT suitable for high-quality lumber. Abdul Khalil et al. (2010) have used OPT and EFB in producing special plywood using phenol formaldehyde. They concluded that hybridisation of EFB with OPT produced a better quality plywood in terms of bending strength, shear strength and screw withdrawal compared to that produced from OPT alone. Pretreatment of OPT veneers with low molecular weight phenol formaldehyde (LMWPF) improves its surface roughness and density in which the plywood produced is able to control liquid penetration to more than 30 s (Loh et al. 2011). Hoong et al. (2012) recently reported on a new method of producing high bonding strength plywood (of 259% stiffness) from OPT using low molecular weight phenol formaldehyde (LmwPF) resin. Other studies (Paridah et al. 2006; Anis et al. 2003; Sulaiman et al. 2009) have also produced high-quality plywood from OPT. Laminated veneer lumber from OPT together with other palm furniture has been produced and on sale in Japan (Abdul Hamid et al. 2005).

The production of binderless particle boards from OPTs (Lim and Gan 2005; Ratnasingam et al. 2008) and steam-exploded pulps and fibres from the OPF (Laemsak and Okuma 2000) has been reported. OPW solid residues have also been utilised for the production of fibreboards as furniture, building and wall-partitioning materials (Wahid et al. 2005).

In most parts of Africa and some parts of Asia, OPLs are traditionally used as roofing and partitioning materials of huts and mud houses. In order to make the roofs durable and strong, clay is used to bind the OPLs to the ceiling beams of the hatches.

Processed palm wood is found to be resistant to termites, mould and wood rot thus makes them applicable for use in both moist and dry conditions. Again, the production of palm wood for furniture is reported to be environmentally safe (emitting about 1.5 kg CO_2/kg product) compared to the production of steel, aluminium and glass with CO_2 emissions of 23.9, 12.0 and 8.4 kg CO_2/kg product (Wahid et al. 2005).

5.3.7 Concrete Materials

In the palm oil mill, the boiler ash (from PPF, PKS and EFB) creates a lot of environmental problems as their disposal methods are unsafe. The ash is normally dumped at landfills without any sustainable means of utilising it. Recent studies have reported many different ways of transforming the palm ash to value-added products such as concrete materials which are used in buildings. Moreover, the quantity of OPW which is not utilised by the boiler as fuel can also be combusted into ash and used for as concrete material. One important benefit of using OPW as concrete materials is that they are organic and therefore do not contaminate or leach out to produce toxic substances once they are bound in concrete matrix.

Ground palm ash would make an excellent pozzolanic material which can be used as a cement replacement in concrete (Chandara et al. 2010; Yin et al. 2008). The replacement of Portland cement type I by 30% palm fuel ash (from EFB, PPF and PKS) gave the compressive strengths of concrete at 90 days higher than that of concrete made from Portland cement type I alone (Tangchirapat et al. 2007). Ismail et al. (2011) have investigated into the residual compressive strength of concrete containing OPW ash after exposure to elevated temperatures and subsequent cooling. The residual performance was found to be higher in OPW concrete than in the normal concrete. Concrete containing OPW as aggregate materials therefore serves as potential building concrete for constructing pavements, floorings and walls.

PKS is used as coarse aggregate in road binder course in order to add more strength to the asphalt concrete (Yusoff 2006; Teo et al. 2007). Concrete with PKS as coarse aggregates has been proven to exhibit good properties in terms of compressive strengths, workability and density (Basri et al. 1999; Shafigh et al. 2012). Recently, a new method has been investigated into by Shafigh et al. (2011) who showed that it is possible to produce grade 30 PKS concrete without the addition of any cementitious materials. Tay and Show (1995) have concluded that the workability, setting times and soundness test results of concrete containing ash from EFB are satisfactory with no segregation. Their results also indicated the high possibility of blending the ash with small amounts of ordinary Portland cement for concrete making without detrimental effects on long-term strength property. Blended cement paste with high fineness OPW ash possesses a higher compressive strength than that with coarse OPW ash (Kroehong et al. 2011).

5.3.8 Biopolymer Composite Materials

The properties of OPW fibres make them suitable for the manufacture of composite biopolymers (e.g. plastics). The pores on fibre surface have an average diameter of 0.07 m which gives it a better mechanical interlocking with matrix resin in composite fabrication (Sreekala et al. 1997). Also, the high cellulose content and high toughness value of OPW make it suitable as composite materials. Lignocellulosic materials such as OPW have the potential to replace synthetic fibres such as aramid and glass fibres in the field of composite material. Though the fibres of lignocellulosic materials have lower density (1.25–1.50 g/cm^3) compared to that of fibre glass (2.6 g/cm^3), they have high tensile strength similar to those in plastic materials and durable compared to synthetic fibre glass (Agrawal et al. 2000). Also, the high carbon and nitrogen contents of palm oil liquid wastes make them suitable for the production of biopolymers for composite materials. Nowadays, fibre-reinforced plastic composites (bioplastics) find many applications in the aerospace and automotive industries, sports and recreation equipment, boats, office products, machinery, etc. (Sreekala et al. 2002).

Polyhydroxyalkanoates (PHA) made from OPW are green biodegradable materials widely used as packaging materials though the cost of production is found to be high. However, through improved process technology (Purushothaman et al. 2001), PHA have been synthesised from OPW by various means using different kinds of bacteria and have many applications in the polymer industry. A two-stage process for the production of PHA from POME has been proposed by some authors in which organic acids (such as acetic and propionic acids) were anaerobically produced (Nor'Aini et al. 1999; Phang et al. 2003; Sim et al. 2009) and converted to PHA by a phototrophic bacterium, *Rhodobacter sphaeroides* IF0 12203 (Hassan et al. 1996) and *Comamonas* sp. EB 172 (Mumtaz et al. 2010; Zakaria et al. 2008). Other authors have reported the synthesis of PHA from EFB (Dovi et al. 2009).

Polyhydroxybutyrate (PHB) and polylactate (PLA) are other bioplastics that can be synthesised from both the solid and liquid residues of the OPW. During PHB production, the OPW is fermented to produce acid which is further fermented to produce the polymer using various enzymes. In PLA technology, sugar is produced from the OPW and fermented into l-lactic acids which are polymerised into PLA resins.

OPWs have also been used in many composite materials including OPW/natural rubber (NR) composites, OPW/polyvinyl chloride composites, OPW/polypropylene (PP) composites, OPW/polyurethane (PU) composites, OPW/polyester composites, OPW/phenol formaldehyde (PF) composites, OPW/polystyrene (PS) composites and OPW/epoxy composites. Polyurethane (PU) composites filled with EFB were prepared using molasses and glycerol-based polyols (Tay et al. 2011) and diphenylmethane diisocyanate and polyethylene glycol (Rozman et al. 2004) matrices. Both reports concluded that good quality PU composites were produced with higher tensile and flexural properties.

The chemical resistance, void content and tensile properties of EFB/jute (natural rubber) composite have been investigated by Jawaid et al. (2011) to be good. The tensile strength of PPF/natural rubber composites as reported by Joseph et al. (2006) and Jacob et al. (2004) is in accordance to the ASTM D 412–68 Standards. It is inferred from their reports that the tensile strength of PPF/NR composite was higher (7.28 MPa) compared to that of PPF/Sisal/NR composites (3.25 MPa).

Lignin obtained from EFB was used as curing agent in green epoxy composites (Kalam et al. 2005) with the conclusion that the EFB/epoxy composite with 25% EFB-based lignin content gave the optimum properties (Abdul Khalil et al. 2011). Synthesis and physico-mechanical properties of OPW fibre-reinforced epoxy composites have been reported by various studies (Kalam et al. 2005; Bakar et al. 2007; Hariharan and Khalil 2005) with conclusions that they possess better characteristics compared to pure epoxy materials.

Benzene diazonium salt has been used in treating OPW fibre to be used as OPW fibre/polypropylene composites (Haque et al. 2009) whose properties are almost similar to coir fibre/polypropylene composites. Other potential applications of PP hybrid composites with OPW include EFB/glass fiber/PU composites (Rozman et al. 2001); EFB/PU, oil palm cellulose/PU composites (Khalid et al. 2008); PPF/PU composite in which the addition of coupling agent in the makes it a promising bio-product as the addition of fibers to the matrix improved the flexural strength and modulus compared to the pure PP (Goulart et al. 2011); PPF/kaolinite/PU composite (Amin and Badri 2007) and EFB/PU composite (Rozman et al. 2007).

The mechanical properties of benzoylated EFB reinforced poly(vinyl chloride) composites have been studied by Bakar et al. (2007) with improved EFB/PVC matrix interfacial adhesion. Thevy et al. (2008) have reported that the thermogravimetric analysis (TGA) have not shown any significant changes in the thermal stability of the composite.

Saline- and alkali-treated PPFs have been used in the synthesis of green composites (PPF/phenol formaldehyde composite) in which the pretreatments increased the thermal stability of the composites compared to untreated PPF (Agrawal et al. 2000). Other authors (Sreekala et al. 2002) have also investigated into the mechanical properties of OPW fibre-reinforced phenol formaldehyde composites. Dynamic mechanical analysis of OPW fibre/PF composite carried out by Sreekala et al. (2002) showed that the incorporation of OPW fibre increased the modulus and damping characteristics of the pure sample.

The tensile strength of OPF/glass fibre-reinforced polyester composites increased up to total fibre content of 45% (Abdul Khalil et al. 2007). The weight loss on abrasion of pure polyester resin is reduced (by 50–60%) by the reinforcement with OPW fibre, whilst the friction coefficient of OPF/polyester composite is reduced by about 23% compared to that of neat polyester (Yousif and Tayeb 2007). The tensile stress of OPF/polyester composites increased slightly upon both acetylation and saline treatments and decreased with titanate treatment (Hill and Khalil 2000).

The modulus of OPW fibre/PS composite is assessed to increase with increase in fibre loading up to 30% whereas the maximum strain and flexural strength decreased (Zakaria and Poh 2002).

Biopolymers such as poly(3-hydroxybutyrate-co-3-hydroxyvalerate) from EFB (Salim et al. 2011) and poly(3-hydroxybutyrate-co-4-hydroxybutyrate) from spent palm oil using *Cupriavidus necator* (Rao et al. 2010) have also been synthesised using various treatment methods. Alkali treatment is the commonest pretreatment of OPW fibres which is able to improve the fibre-matrix interfacial adhesion.

5.3.9 Activated Carbon, Catalysts and Adsorbents

Preparation of activated carbon from EFB by microwave-assisted KOH activation for methylene blue adsorption (Foo and Hameed 2011), PKS by phosphoric acid impregnation (Lim et al. 2010), PKS by $ZnCl_2$ and physical activation for methane adsorption (Arami-Niya et al. 2010; Abbas and Daud 2009), PKS to remove lead ions from aqueous solutions (Issabayeva et al. 2006), PKS for basic dye adsorption (Jumasiah et al. 2006), OPT by phosphoric acid impregnation (Hussein et al. 2001), PKS by chemical activation with K_2CO_3 (Adinata et al. 2007) and PKS by $ZnCl_2$ impregnation for the removal and recovery of residual oil from POME (Ngarmkam et al. 2011) have been reported. The results from Arami-Niya et al. (2010) indicated a significant increase in methane adsorption after physico-chemical activation. Preparation of palm oil empty fruit bunch-based activated carbon for removal of 2,4,6-trichlorophenol has also proven feasible (Hameed et al. 2009). Catalytic characteristics of activated carbon manufactured from PKS for methane decomposition were studied using a thermobalance (Abbas and Daud 2009).

The development of microporosity for the oil-palm-shell activated carbon would lead to potential applications in gas-phase adsorption for the removal of air pollutants (Guo and Lua 2002). Tan and Ani (2004) utilised PKS to prepare carbon molecular sieve (CMS) by carbonisation for air separation and concluded that PKS is a highly potential material for CMS. Other studies (Ahmad et al. 2008; Adinata et al. 2007; Sumathi et al. 2010) have also utilised PKS and other OPW as activated carbon for gas removal. Some other applications of OPW for carbon materials include high porosity carbon powder from OPW as an adsorbent (Alam et al. 2009; Tan et al. 2010), carbon glassy from PKS for electrodes (Aroua et al. 2008), green nanoparticles from POME (Gan et al. 2012) and electrical carbon brushes as conductors.

5.3.10 Other Value-Added Palm Products

5.3.10.1 Textiles and Woven Household Materials

Most indigenous areas of Africa and Asia have been using OPL petioles for weaving mats, baskets, fans, hats, sacks, carrier bags, etc. Due to lack of technical know-how and capital cost of producing these materials in commercial quantities, their potential uses have been nipped in the bud.

Also, useful cord or rope is made by rolling OPL into strands which are further used to tie thick bands of items. The OPL strands are again useful in making nets for transporting cargo and forage. Net for catching fish is also made traditionally from OPL. OPW fibres are also used to stuff mattresses, sofa, etc.

5.4 Simultaneous Production of CPO and Utilisation of OPW for Value-Added Bio-Products

The amount of OPWs that are used for mulching and nutrient recycling are more than necessary. Large quantities of OPFs, OPLs, OPTs and OPRs which are underutilised can be effectively used in applications such as bio-fertiliser production, food and feed production as well as biomass power plant to generate

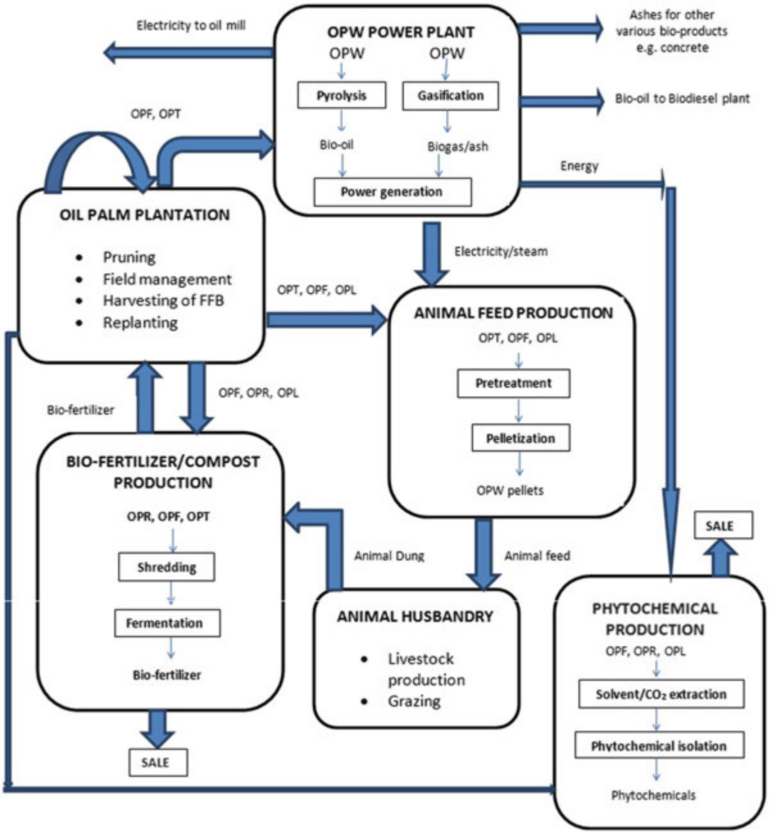

Fig. 5.2 Simultaneous production of FFB and utilisation of OPW for various value-added bio-products incorporating animal husbandry

electricity. Figure 5.2 summarises the simultaneous production of FFB and utilisation of OPF, OPL, OPR and OPT for power generation and feed production around the palm plantation.

The concept of integrating animal husbandry into palm oil plantations is found to be feasible as demonstrated by Jalaludin 1996. Usually, pesticides and weedicides from inorganic (chemical) sources are used to control weed growth and insect attacks in the palm oil plantation. These are environmentally unsafe and cost ineffective and can be totally eliminated when livestock production is incorporated in palm oil plantation whereby forages in the inter-rows grazed off by the livestock. Also, the dung from the animals could be used as organic fertiliser in the plantation hence reducing the cost of FFB production and soil nutrient deterioration. Excess dung could be processed in the bio-fertiliser production unit for subsequent sale. Figure 5.3 shows the schematic diagram of the conversion of OPW in the palm oil mill into value-added bio-products.

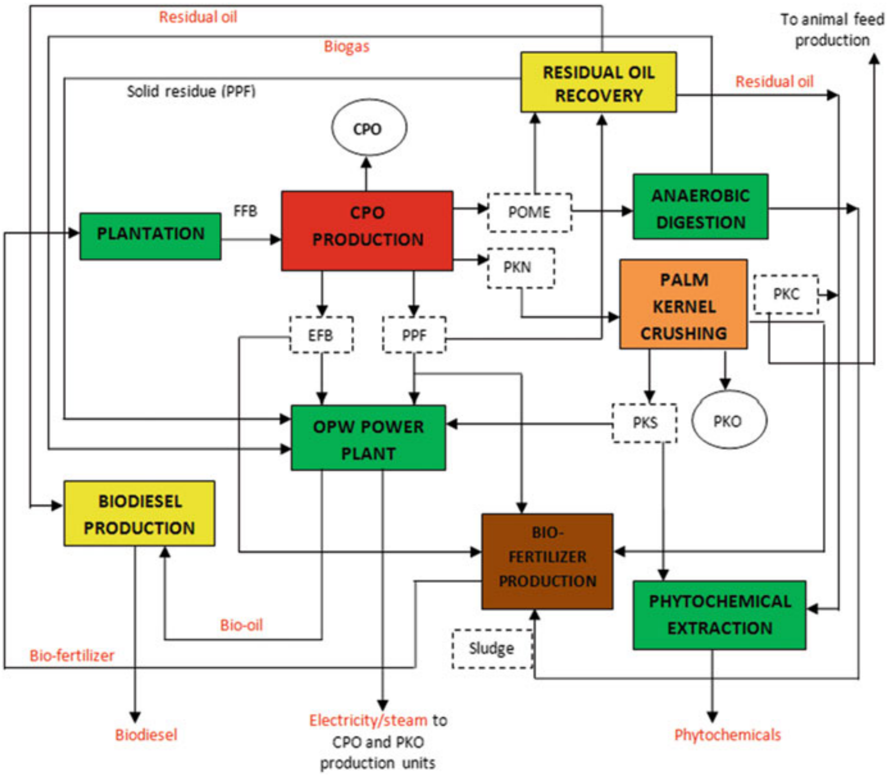

Fig. 5.3 Schematic diagrams of the simultaneous production of CPO and conversion of OPW into value-added bio-products

5.5 Conclusion

OPW can be utilised efficiently into green wealth by simultaneously transforming some of the wastes into energy to be utilised by the various value-added bio-product production units within the palm oil industry. Converting OPW into bio-products could evolve a lot of creative technologies and industries which would further jobs and improve the life of people in the palm oil-producing countries. Industries such as food, phytochemical, furniture, polymer and composite materials, activated carbon, soap and cosmetics and power plants could be set up as integration into the palm oil plantation and palm oil mill for the benefit of mankind.

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